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Physio-Med Web: Real Time Monitoring of Physiological Strain Index (PSI) of Soldiers During an Urban Training Operation

Reed W. Hoyt, Ph.D.
Research Physiologist
U.S. Army Research Institute of Environmental Medicine
Natick, Massachusetts 01760-5007
United States of America

Mark Buller, B.S.
Geo-Centers, Inc.
190 North Main St.
Natick, Massachusetts 01760
United States of America

Stan Zdonik, Ph.D.
Professor of Computer Science
Brown University
Box 1910, Computer Science Department
Providence, Rhode Island 02912
United States of America

Chris Kearns, B.S.
Chief, Dismounted Battlespace Battle Lab
Bldg. 4, Rm. 347
Ft. Benning, Georgia 31905
United States of America

LTC Beau Freund, Ph.D.
Deputy Commander
U.S. Army Research Institute of Environmental Medicine
Natick, Massachusetts 01760-5007
United States of America

COL John F. Obusek, D.Sc.
Commander
U.S. Army Research Institute of Environmental Medicine
Natick, Massachusetts 01760-5007
United States of America

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Summary

This field study of simulated urban combat explored the array of issues associated with the collection and use of real-time physiologic data. Six male soldiers (age = 22±4y [mean±SD]; ht = 172±5 cm; wt = 69.3±11.6 kg; %body fat = 13.9±6.9; load carried = 19.0±2.9 kg) were monitored in real-time during a simulated attack on the McKenna Military Operations in Urban Terrain (MOUT) facility at the Dismounted Battlespace Battle Lab, Ft. Benning, Georgia. Physiological strain index (PSI), derived from heart rate (HR) and core temperature (Tcore), was used to monitor thermal/work strain (Moran et al., Am. J. Physiol. 275:R129-R134, 1998). Meteorologic conditions: air temp = 21 to 24 ^{o}C; relative humidity = 55-65%; solar radiation = 150-430 W/m ^{2} (estimated WBGT = 19 to 23 ^{o}C). Methods: Tcore was measured by ingested radio telemetry pill, and HR was measured electrocardiographically. Data from these ambulatory sensors was transmitted through a wireless personal area network (PAN) to a control facility where the PSI of each soldier was displayed during the two hour simulated attack. Results: initial PSI = 2 (range: 0 to 3.5), peak = 5 (3.5 to 6.5), recovery = 3.5 (2 to 5). Heart rate (HR): initial = 80 bpm (60 to 110), peak = 165 (140 to 185), recovery = 105 (95 to 125). Core temperature: initial 37.5 ^{o}C (36.8 to 37.9 ^{o}C), peak = 37.9 ^{o}C (37.3 to 38.5 ^{o}C), with limited decreases with 30 min of recovery. Conclusions: PSI appears to be a sensitive indicator of cardiovascular and thermal strain; real-time PSI has potential value in military operations where heat strain is a significant risk. However, significant sensor, PAN, and data management and modeling work remains to be done before the routine use and dissemination of physiologic information is practical for the dismounted warfighter.

Introduction

This study explored the array of issues associated with the collection and use of real-time physiological strain index (PSI) data from soldiers engaged in simulated urban combat. This work was part of a larger "Smart Sensor Web" study exploring broad issues of sensor data management in an urban battlefield.

In most scientific studies, ambulatory sensor data is stored for post hoc analysis. However, near real-time physiologic data collection and analysis is needed for certain militarily and civilian applications. In particular, combat casualty care needs real-time monitoring for remote detection of ballistic wound events, remote life sign detection, and remote triage. Thermal/work strain monitoring may also be useful for warfighters, space flight personnel, firefighters, or civilians working under thermally stressful conditions.

The US Army's need for physiological monitoring, the current approach to thermal/work strain management, and the Department of Defense heat stoke/sun stroke injury rates are noted below. In addition, the PSI and the issues associated with real-time collection and use of ambulatory physiologic data are discussed. These include: (a) designing comfortable wearable sensors that reliably collect, process, and output Tcore and HR data, (b) implementing wireless Personal Area Network (PAN) transmission of sensor data to a central hub for storage and long range re-transmission to a central control facility, and (c) developing new data base and data mining techniques to manage the large amounts of time series information generated by wearable monitors.

Overview of physiological data requirements and current doctrine

From a broad perspective, military field commanders, medics and, perhaps most importantly, individual warfighters need operationally-relevant performance and health status indicators to avoid casualties. When combat casualties occur, remote life sign detection and remote triage capabilities are needed. In particular, new approaches are needed to improve sleep management, ensure adequate water intake, improve thermal/work stress management, and avoid heat and cold injuries.

Thermal/work strain is typically managed through work/rest cycle and water intake guidance. For example, in the US Army Field Manual 21-10, a table of Fluid Replacement Guidelines for Warm Weather Training shows work/rest cycles and water intakes for various heat categories and WBGT indexes (Table 3-1 on page 3-4 of Field Manual FM 21-10; http://www.adtdl.army.mil/cgi-bin/atdl.dll/fm/21-10/fm21-10.htm). However, in reality, these guidelines are often not followed when there is a hot weather mission to perform. Water availability may be limited, and water consumption may not be adequately monitored. The consequence is a steady stream of serious and costly heat injuries.

Heat stroke/sun stroke injury rates can be estimated from the Defense Medical Epidemiological Database DMED data base (http://amsa.army.mil) for a population of about 1.39 M warfighters from all services. Over the past 10 years, there have been about 878 heat stroke/sun stroke injuries, with the majority from the Army (511) and US Marine Corps (300). Over the past three years (1998-2000), 384 heat stroke/sun stroke injuries have occurred. Current estimated cost per affected soldier is US$132,000, based on duty days lost, and the cost of hospitalization, replacement, and disability. In terms of dollars alone, this is roughly a US$10M/y problem. Clearly, exploring the use of PSI, and developing new ways to manage thermal strain and reduce heat casualty rates, is warranted.

Physiological Strain Index (PSI) algorithm

The physiologic strain index (PSI), derived from core temperature (Tcore) and heart rate (HR), is simple to calculate, and is uniquely suited to real-time "on-the-fly" monitoring of thermal/exercise heat strain. The PSI reflects combined cardiovascular and thermoregulatory strain on a universal scale of 0 to 10 (13), and appears sensitive to the various influences of climatic conditions, clothing, exercise intensity, hydration state, age, and gender (see Pandolf and Moran, in these proceedings). The PSI algorithm assumes maximum acceptable increases in Tcore and HR of, 3 ^{o}C (36.5 ^{o}C to 39.5 ^{o}C) and 120 beats/min (60 to 180 beats/min), respectively. These upper limits reflect Tcore and HR bounds defined by the USARIEM Institutional Review Board for directed experiments with humans. The two constants "5", preceding the two main terms of the index, reflect the equal influence of Tcore and HR on PSI. That is,

$$PSI = 5(Tcore_t - Tcore_0) \times (39.5\text{-}Tcore_0)^{-1} + 5(HR_t - HR_0) \times (180\text{-}HR_0)^{-1},$$

where Tcoret and HRt are simultaneous measurement taken at any time during the exposure, and Tcore0 and HR_0 are baseline measurements (13).

Core temperature and heart rate sensors

Pulmonary artery, esophageal, and rectal temperatures are valid and widely accepted ways of measuring Tcore (8, 16, 18), but are not suited for use in ambulatory individuals. Tcore estimates by tympanic and axillary temperatures are imprecise (7) and likely to be affected by the variable microclimates experienced by soldiers. Fortunately, telemetry pills provide a valid and field-expedient method of measuring Tcore. Ingested telemetry pill temperatures, under conditions of rising and falling body temperature, closely correlate with esophageal and rectal temperatures (15).

The thermometer pill used in the present study is a very low power radio frequency transmitter where broadcast frequency (~260 kHz) varies with temperature (U.S. patent No. US4844076, issued Aug. 26, 1988; CorTemp™, Human Technologies Inc., Palmetto, FL; www.htitech.com).

This simple analog approach has two key problems. First, pill calibration data must be tracked, since each pill has a unique calibration curve that relates received frequency to temperature. Second, these pills broadcast on a similar frequency, resulting in cross-talk among test volunteers in close proximity. Due to this potential for interference, pill receivers cannot be too sensitive, and only one sensor can be used on a give individual.

To address these problems, an improved microprocessor-controlled thermometer pill is being developed with US Army support. This new telemetry pill should be smaller, less expensive, easier to use, and more capable. In contrast to the current analog system, the new digital temperature sensors will broadcast actual temperature and a unique identifier, making it possible to use multiple skin and core temperature sensors on a given individual (Mini Mitter, Inc., Bend, Oregon; www.minimitter.com).

In the present study, heart rate (HR) was derived electrocardiographically using adhesive electrodes. Over more extended periods of wear, approaches using methods that do not involve adhesive electrodes or potentially uncomfortable chest straps would be more appropriate.

Personal Area Network (PAN)

The ability to connect a variety of body-worn sensor through a PAN is particularly critical for combat casualty care activities such as remote wound detection, remote life sign detection, and remote triage. A successful PAN must be comfortable, low power, lightweight, and not produce electromagnetic signatures that can be used to detect the location of the wearer. Furthermore, PANs must be rugged, reliable, compatible with a variety of garments and body worn equipment. However, this level of functionality is difficult to achieve in field environments where power, weight, and bandwidth are limited, and operating conditions are often harsh due to vibration, shock, immersion, and temperature extremes.

In the present study, sensor data was routed via a PAN to a central data processing point, or hub, where digitized data was stored and re-transmitted via off-body telemetry (Model DRG-115; Freewave Technologies, Boulder, Colorado; http://www.freewave.com). The PAN used commercial components (model TR3001; RF Monolithics, Inc., Dallas, Texas; http://www.rfm.com) to push data to a central hub. That is, the sensors periodically and redundantly transmitted data to the hub receiver. Collisions between data packets occurred, but the slow data rate needed to monitor HR and Tcore changes allowed this simple approach to succeed. This PAN is typical of most other existing PAN technologies - that is, somewhat primitive and based on an ad hoc design that has a tendency to be brittle and error-prone. Alternate approaches using wired PANs risk snagging or connector failure and tend to restrict sensor and processor placement. Wireless RF PANs, such as Bluetooth, are detectable at ranges of 10 km by electronic intelligence systems and yet may be locally unreliable due to blockage by the user's body. Alternatives to wired and conventional RF PANs, such as short-range PANs using free space magnetic induction and inherently short range propagation and low power consumption, have yet to be explored.

Beyond basic hardware issues, there is an enormous gap in our toolkit of software techniques for constructing such systems, particularly with respect to reliability, dynamic reconfiguration, and intelligent data management in low-bandwidth and limited storage situations. Given inherent PAN bandwidth constraints, innovative approaches to data management in the network will be a crucial technology for achieving scalability in this type of system. Such technologies would address issues of data storage and retrieval as well as the management of data flow through the network. We will have more to say about these problems later.

Data Management

Managing large time series data sets quickly and effectively can be nettlesome and time consuming. This is consistent with Lewis's point of view (10) that the "bottle neck" in scientific production is not the basic science, but the ability to deal effectively with the data. The approach of manually formatting and merging data files, and writing ad hoc software to process new and different file types was too time consuming. To solve this problem, we characterized the various data types, organizing these data types into a comprehensive archive, and developed simple yet powerful software routines to access subsets of data. This automated approach depends on two elements: a standardized representation of data, and software tools that use this representation to quickly view and export selected data for further analysis.

Data standardization - Typical field study data includes an array of data types - ranging from weather to clothing characteristics to physiologic data (Table 1). The exact characteristics of field data sets varies from study to study.

Table 1. Typical field study data types, sampling intervals, and data persistences.

Data Type	Collection Interval	Data Persistence
Core Temperature	1 min	Instant
Heart rate	Beat-to-beat	Instant
Geo-location	2 sec	Instant
Meteorologic	15 min	15 min
Clothing log	60 min	60 min
Equipment log	60 min	60 min
Video	Sporadic	Length of clip
Photographic	Sporadic	Instant
Activity log	60 min	60 min
Weight	24 hour	24 hour
Biographic	Once	Study
Comments	Sporadic	Instant/range

In spite of the variety of data types, automated data analysis was possible given that the formats of all the data were known. However, the challenge was to develop generally useful data analysis tools that could be used when the number and types of sensors changed, and new research questions resulted in new types of data queries.

Data Characterization. Most data archiving schemes are based on known schema. These schema are captured in a standard data model such the relational model, object/relational models (2, 4, 10, 11, 21), flat file schemes (2, 6, 10, 11, 21), hierarchical data models (21), and hybrids (2). Each model has its advantages and disadvantages for archiving data but none addressed the fundamental problem of organizing sets of data with unspecified structures. In the current implementation, the flat file method of archiving data seemed to offer the most promising route for organizing such an extensible data set.

The flat file method had been used with some success in certain bibliographic and complex protein sequence databases (1, 5, 6). The use of tagged data items and ASCII text in these databases offer many advantages. Tagging data means that a loose file structure can be maintained, new types of data can be added without compromising the data archive, and data are readily accessed by investigators (6). Tagging of data is not new and has been employed in the Standard Generalized Markup Language (SGML), an international standard (9, 20) widely used for document management. A subset of SGML called extensible markup language (XML) is commonly used for data sharing between businesses, and is increasingly being used by the World Wide Web community. The XML format was a natural choice for an extensible and standardized way of representing our field study data streams.

The problem of encoding data within XML was first approached by examining and enumerating both the types of data, and the types of questions to be addressed by the data. Secondly, the data types were abstracted and broken down into key components. Through this process, five identifying properties were found to characterized each data point: location, time, temporal persistence, to whom or what the data related, and what the data represented. These five properties allowed the data to be represented by three key axes - space, time, and entity - on which data can be collapsed or expanded.

Relational Database Systems are notoriously bad at handling time-series data. To help address these time series data management problems, a prototype Data Visualization/Data Mining tool (DVDM) was developed to read and mine (extract data) from time-series XML data archives. The DVDM tool is generic and generally usable as long as data are represented as objects within the XML format. Context as to what the experimental data measure is provided by the experimenter. The tools is based upon time granulizing all data, and resolving what data exist or are valid for a given time granule. The software also allows users to select the preferred method of dealing with multiple data points within a time granule. Entity-to-data relationships are also resolved. Thus data can be viewed and collapsed by time slice and entity (subject). Queries can also be made on any type of data, and multiple queries can be stacked. The DVDM also allows queries across time, and once pertinent periods of time are identified, data can be exported for further analyses by statistical, graphical, and other analytical tools. Although the DVDM will work with any time resolution, the amount of data that can be analyzed at a given time is limited by the working memory (RAM) of the computer being used.

Results

The following figures show meteorologic data, and physiologic data collected in real-time from six male soldier (age = 22±4y [mean±SD]; ht = 172±5 cm; wt = 69.3±11.6 kg; %body fat = 13.9±6.9; load carried = 19.0±2.9 kg) during a simulated attack on the McKenna Military Operations in Urban Terrain (MOUT) facility at the Dismounted Battlespace Battle Lab, Ft. Benning, Georgia. Meteorologic conditions were temperate (Figure 1) with an estimated WBGT (wet bulb globe temperature) of only 19 to 23 °C. The WBGT was estimated from air temperature, relative humidity, and solar radiation (14).

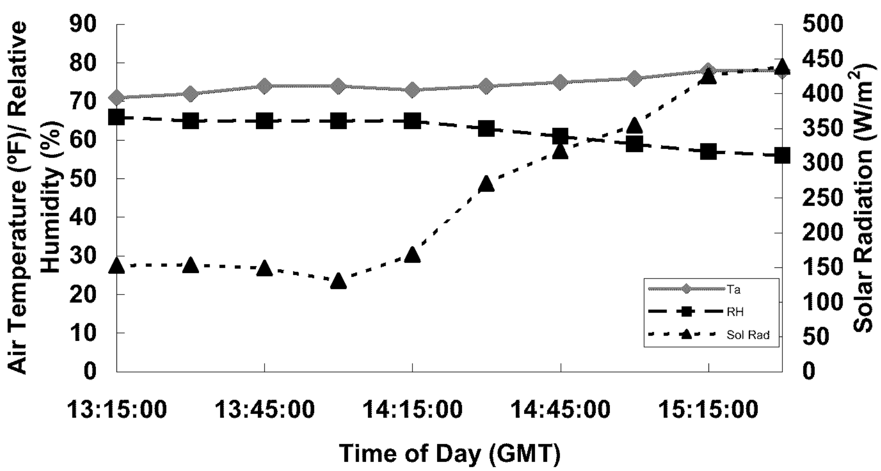

Figure 1. Meteorological conditions (air temperature, relative humidity, solar radiation) during the simulated attack in an urban setting.

The mission consisted of a simulated attack by a squad of soldiers on an opposing force ensconced in the single and multi-story buildings of the McKenna MOUT facility at the Dismounted Battlespace Battle Lab, Ft. Benning, Georgia (see http://192.153.150.25/dbbl/dfd/mkenins.htm). All soldiers were equipped with MILES (Multiple Integrated Laser Engagement System). The general route of the attack within the McKenna MOUT facility is shown in Figure 2. Changes in Tcore, heart rate, and PSI during the simulated attack are shown in Figures 3 to 5, respectively.

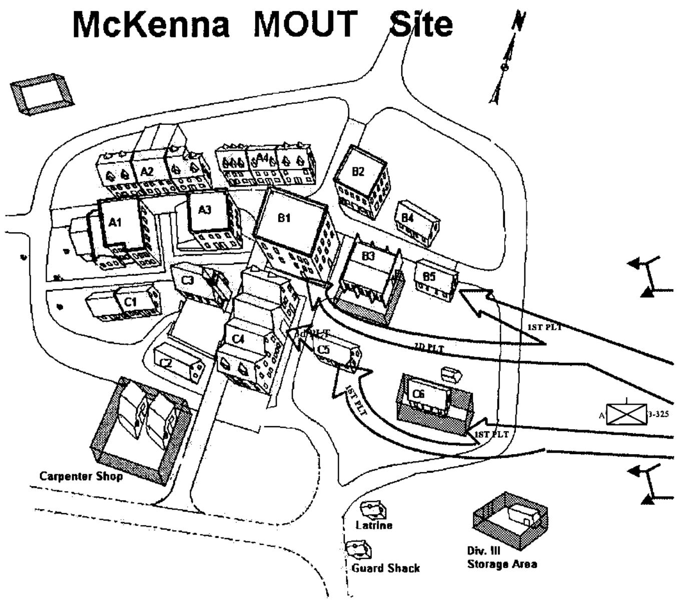

Figure 2. Arrow show the route of the simulated attack at the McKenna military operations in urban terrain (MOUT) training facility.

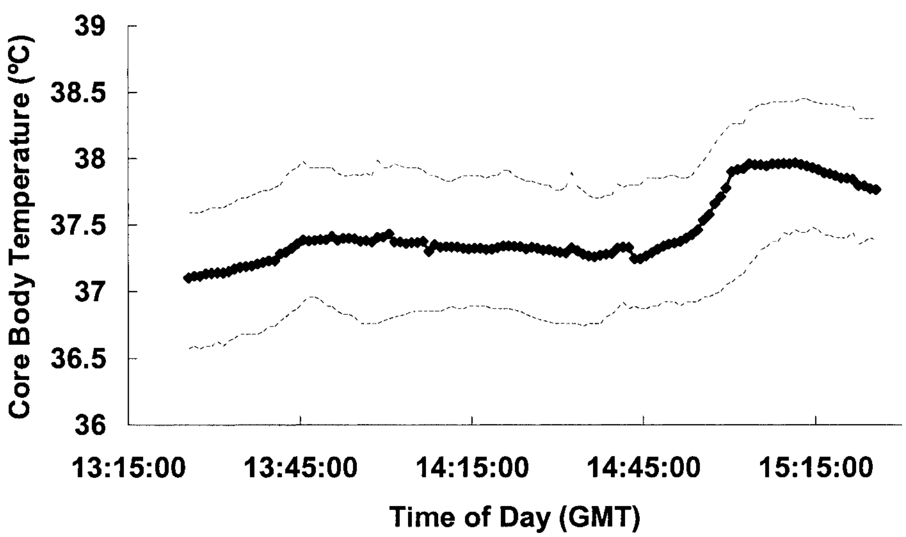

Figure 3. Core temperatures (mean ± range) as measured by ingested telemetry pill and monitored in real time during a simulated attack at the McKenna military operations in urban terrain (MOUT) training facility.

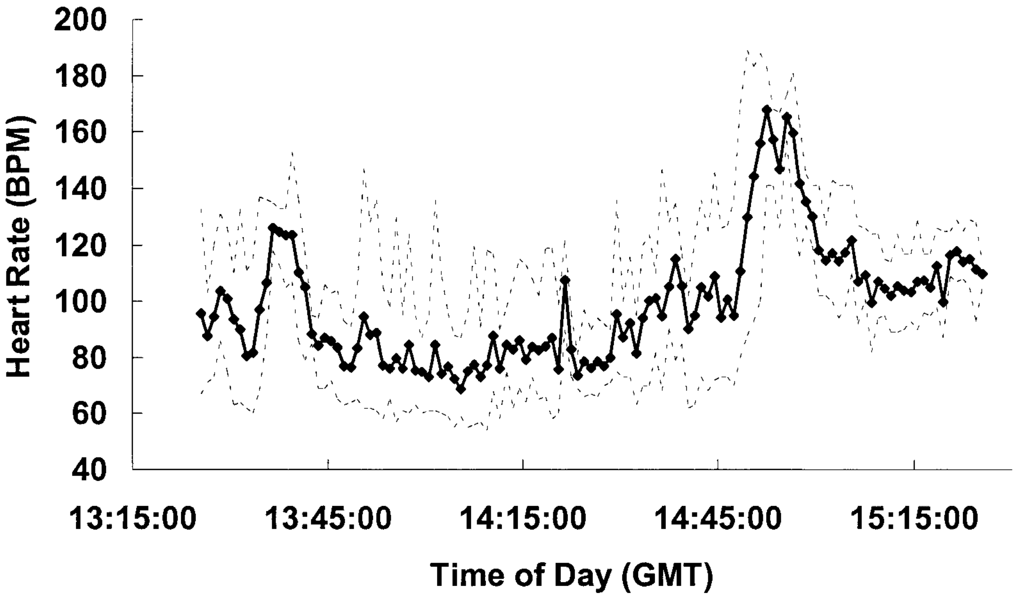

Figure 4. Heart rate (mean ± range) by electrocardiogram and monitored in real time during a simulated attack at the McKenna military operations in urban terrain (MOUT) training facility.

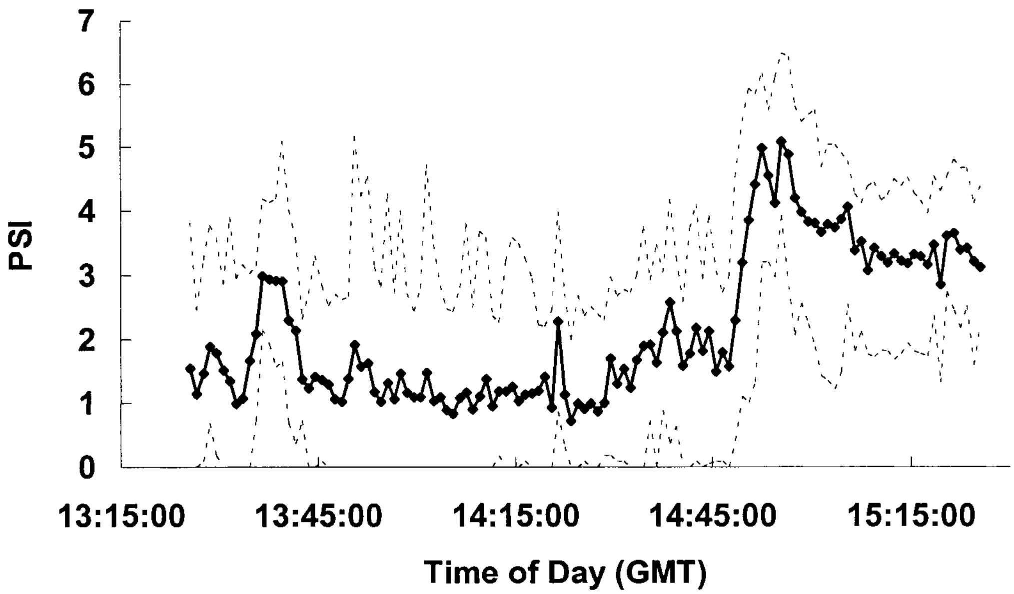

Figure 5. Physiological strain index (PSI) (mean ± range), calculated from heart rate and core temperature, during a simulated attack at the McKenna military operations in urban terrain (MOUT) training facility.

The PSI data was transmitted to and displayed at the control center of the MOUT training facility. Although the soldiers were equipped with wearable computers (Xybernaut Corporation, Fairfax, Virginia; http://www.xybernaut.com), technical problems prevented transmission of the PSI data to the soldiers. Instead, the squad leader intermittently viewed PSI data and other tactically useful sensor data by entering the control facility (PSI data from the less physically active squad leader is not presented). The current and historical PSI for each individual soldier was displayed in the control facility (data and data display are on USARIEM's web page **http://www.usariem.army.mil/wpsm/demo/wpsmview.html**). However, it seems that physiologic data that helps soldiers avoid becoming environmental casualties would be most useful locally, that is, to the individual soldier, the squad leader, or the platoon medic. The relatively wide range of PSI among the soldiers probably reflects individual differences in tasks being performed, load carried (16 to 24 kg), and differences in heat acclimation and physical fitness - two factors that significantly affect tolerance of heat stress (17). The slow decline in PSI post mission suggests repeated bouts of exercise could lead to thermal strain even under temperate conditions.

Discussion: The Need for a New Approach to Data Management

Data management has long been the province of database management systems (DBMSs). Modern DBMSs are quite impressive when dealing with huge amounts of data with very regular structure; however, they are not as well suited to less predictable environments that are dominated by time-series data. They were not built with time-series data management as a goal, and as a result, the underlying access methods were designed to support set-at-a-time processing as is represented by the SQL (12) query language. Structuring the underlying database and forcing SQL to work efficiently with temporal data is a difficult if not at times impossible process (19), with simple time-series operations such as time-based merging, interpolation, extrapolation, and time-based aggregates (e.g., windowed average) being unsupported.

On the other hand, it is our strong belief that sound principles of data management can be successfully applied to setting such as ours to achieve high-performance in the face of resource restrictions. Given the complexities of the sensor-based environment, it is difficult to see how a more extensive and less controlled deployment could succeed without a reasoned approach to the intelligent management of physiological data. We are beginning to investigate the proper structure for a data management infrastructure that will allow for extensible, reliable, and scalable processing of sensor data. This study involves identifying the appropriate software primitives and a workable software architecture for tying them together. We aim to design primitives that can be used at all levels of the sensor network - from the sensors themselves and the local soldier-based processing hubs, up to and including the centralized archiving facilities.

Sensors produce ordered, append-only data structures that we will call *streams*. These streams must be produced by filtering, aggregating and combining sensor data as it is generated. The processing of multiple input streams can be expressed as a query that is analogous to a query written in SQL for relations. Processing requirements expressed as a query allow the system to apply optimization techniques. One of the major differences between our system and a standard DBMS is that streams must be processed as new data items are produced. The answer to a stream query is always evolving. Queries of this kind have been called *continuous queries* (3) since they are continuously evaluating their inputs. Continuous queries over time-series data (streams) will be a key part of a data management facility that can dynamically adjust its processing strategies to best fit the current demands of the network.

Data management is typically driven by careful assessment of application needs. For the DBMS, this is done by a Database Administrator (DBA) who is responsible for understanding possibly conflicting application requirements and for tuning the DBMS accordingly. In a highly dynamic and large-scale environment, this approach is not feasible. Instead, the users and/or the applications must pre-declare their data requirements along with their relative priorities. Such declarations are called *profiles*. In particular, a user's profile should be able to specify characteristics of the individual that might affect the way in which data is collected and moved through the PAN. For example, if a user were known to have a propensity for heat injury, PSI monitoring would be given a higher priority.

Based on these profiles, the system can make data management decisions that use available resources for the maximum benefit. For example, more important items can be scheduled for transmission before less important items, data reporting rates can be reduced when no application needs higher ones, and caching can be used to decrease retrieval latency of popular items.

The combination of stream-based queries with a sophisticated application profiling facility provides the conceptual framework on which a data management substrate can be built. This substrate can automatically adjust its processing strategies (optimization) with respect to how the system uses cache space, orders the delivery of information, sets appropriate data rates, and chooses the most efficient algorithms for the evaluation of queries. It will also be able to make intelligent choices about how sensor data should be stored in order to support efficient future retrieval.

Conclusions

- This study suggests physiological monitoring could be used to reduce environmental injuries among soldiers. Specifically, near real-time monitoring of PSI could be used to reduce the incidence of heat injuries in military operations where work/heat strain is a significant risk.
- Remote physiological monitoring is also needed to support remote combat casualty care activities such as remote wound detection, remote life sign detection, and remote triage.
- However, significant sensor, PAN, and data management and modeling work remains to be done before the routine collection, dissemination, and use of physiologic information is practical for the dismounted soldier.

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Disclaimer

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